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Effects of trees and termite nests in agroforestry parklands on preferential water flows:

image analysis of soil profiles after rain simulations and dye experiments

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Effekter av träd och termiter på preferensiellt vattenflöde i agroforestry parklands:
bildanalys av markprofiler efter experiment med regnsimulering och infärgning

Addisu Almaw Semeneh

Nyckelord / *Keywords:*
Preferential water flow, macro pores, infiltration capacity, termites, *Vittelaria paradoxa*, tropics, Burkina Faso, brilliant blue tracer

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Abstract

Water scarcity is a critical problem in semi-arid tropics of Burkina Faso. Agroforestry parklands, a land use where scattered trees are maintained with annual crops, is commonly practiced by farmers in which termite nests are integral components of the system. This study intended to assess the effects of proximity to trees and termite nests in agroforestry parklands on preferential flow in soils using image analysis of soil profiles after rain simulations and dye-tracer experiments.

The measurements were conducted in six transects: three corresponding to small openings (20-30 m) and three to large (77-127m) openings. Within each transect in three positions: next to tree, a tree with a termite nest and center. Each vertical soil profile has size of 500 mm width by 500 mm depth. The images were classified in Erdas Imagine 9.3 and preferential flow parameters (absolute slope sum, uniform front depth, total stained area and others) were defined from the dye infiltration pattern to assess the degree of preferential flow in different positions.

The results indicated that the degree of preferential flow significantly decreased from trees with as well as without termite nest to the openings. Preferential flow in tree with termite nests was significantly higher than in the openings. Preferential flow under trees without a termite nest did not significantly differ from trees with termite nests and openings with exception of absolute slope. The water inflitrability was not significant with treatment effect and distance to the nearest tree and termite nest, not related to degree of preferential flow. The opening size effect was significant with absolute slope and close to significance with uniform front depth. Maintaining trees and termites nest in the agroforestry parklands can help in improving preferential flow and may enhance groundwater recharge.

Keywords: Preferential water flow, macro pores, infiltration capacity, termites, Vitellaria paradoxa, tropics, Burkina Faso, brilliant blue tracer

Table of Contents page

1. Introduction

1.1. Agroforestry parklands, termites and preferential flow

Burkina Faso is a country in semi-arid tropical region of West Africa. According to Simonsson (2005), the country has high water scarcity with ninety percent of the population relying on subsistence agriculture, primarily of agroforestry parklands.

Agroforestry parklands are traditional farming systems, characterized by a deliberate retention of multipurpose scattered trees on the farm land with associated annual crops/fallow (Boffa, 1999). It is a system widely practiced by small holder farmers in semi-arid West and East Africa. The trees are purposefully selected and maintained when converting the woodland to farmland (Teklehaimanot, 2004; Bayala et al., 2011) for range of ecological and socio-economic benefits.

The parkland trees have the potential to improve soil physical and chemical properties (Boffa, 1999; Jonsson, 1999). Trees enhance soil physical properties such as soil structure, porosity and moisture retention (Nair, 1993). Moreover, trees supply organic matter which stabilizes soil aggregates and support soil macro fauna activity. The improvement in soil structure and soil macro fauna activity enhances soil macro porosity, which in turn enhances preferential flow. Breman & Kessler (1995) found out that infiltration under tree canopy is higher because of the soil macrofuana created macropores and micropres.

Shea butter tree, also known as Karité (*Vitellaria paradoxa C.F.Gaertn*.), is the principal parkland species in Burkina Faso. Farmers keep the tree on their farm for its products (wood, food, fodder, medicine) and the income they get from the nuts. Shea butter produced from the kernels of the tree nuts is used as cooking oil for subsistence and represents an important income when selling the product in local and international markets (Teklehaimanot, 2004).

It has been reported a decrease in the density of karité trees in the parklands in Burkina Faso (Gijsbers *et al.*, 1994) as a result of high population pressure, high browsing and increasing drought and intensification of agriculture (Gray 2005). High density of trees on the farm is likely to have negative effects on crops because of the increased water consumption by trees (Malmer et al., 2010).Trees, however, have positive effects like the modification of the microclimate and fertility under the canopy through shading, leading to decreased temperature and evaporation losses and higher moisture content (Sanou et al., 2010), and the increased soil infiltrability (Ilstedt et al., 2007; Hansson, 2006). Nevertheless, the net effect of trees on the water budget depends on the delicate balance between the increase in infiltration and the amount of water used by trees.

Experiments on the effect of the parkland trees on cereal yield conducted for sorghum and millet in Burkina Faso show that the amount of rainfall is a decisive factor. In high rainfall seasons, the cumulative positive effect of scattered trees of néré (*Parkia biglobosa*) and karité (*Vitellaria paradoxa*) outweighs the negative effects of shading on millet yield (Jonsson et al., 1999; Gnankambary et al.,2007). On the other side, Boffa et al. (2000) found that the sorghum yield decreased under the karité in comparison to the open field in below average rainfall in Southern Burkina Faso.

Even though, there is gap of knowledge on the overall effects of karité trees on the crops, recent studies highlight that infiltration capacity under the tree canopy might be higher. Joelsson (2012) showed that infiltration capacity under trees was higher compared to open fields due to an improvement in soil structure as demonstrated by a lower bulk density and an increased amount of macropores in saponé, central Burkina Faso.

Termites are essential soil macro fauna in the arid and semi-arid ecosystems. Termite activity can have noticeable influence on the soil physical and chemical properties through formation of nests, galleries and mounds. Among the soil physical impacts we can find changes in soil structure, texture, bulk density and water inflitrability; soil chemical impacts include changes in organic matter, pH and macro-nutrients (Jouquet et al., 2011; Lobry de Bruyn,and Conacher, 1990).

Research on the role and impact of termites is mainly focused on their function in the ecosystem, with little attention on their effect on preferential flow. Large macropores formed by termites can significantly increase water infiltration and enhance water storage

(Léonard, 2004; Léonard & Rajot, 2001). The effects of termites would be more profound around the nests/mound areas since termites are social soil engineers. Trees regeneration tends to concentrate around termite nests (Traoré et al., 2008) most likely in connection to better fertility and water content. Turner (2006) found that termite colonies act as ‘’water gathering systems’’ in semi-arid savanna ecosystems by trapping water from a wide area towards the nest, and enabling water availability to associated organisms (e.g. trees) during dry periods. Termite activity is also acknowledged as a means of site restoration. Mulching/organic matter supply triggers termite activity, degrading soil crust and enhancing infiltration in the Sahel (Mando et al., 1996).

The presence of trees and termites in the farm is likely to enhance preferential flow by improving macro porosity of soil through supply of organic matter and bioturbation with associated improvement in soil macro organisms. The roots of trees are important means of preferential flow (Devitt & Smith, 2002).

Burkina Faso, like other seasonally dry African countries, is very vulnerable to the impact of climate change. The rainfall is highly variable- in amount, location, timing and from year to year, which makes water supply a problem (Simonsson, 2005). This variation will be substantial with anticipated climate (IPCC, 2007). The resilience to the impacts of climate change can be jeopardized by poverty, frequent drought, inequitable land distribution and dependency on rain fed agriculture (Simsonsson, 2005). This will have great influence on water availability to people and plants.

Understanding the role of trees and termites in agroforestry parklands on preferential flow in Burkina Faso can help us know their influence in groundwater recharge, which is important to design appropriate management practices to enhance water availability and thus mitigate the effect of climate change.

1.2. Objective of the thesis

Assess the effects of proximity to trees and termite nests in agroforestry parklands on preferential flows in soils by image analysis of soil profiles after rain simulations and dye-tracer experiments.

1.3. Hypotheses

A. The degree of preferential flow decreases with distance to closest tree and termite nest

B. Trees with termite nest have more macro pores and preferential flow than trees without.

C. Water inflitrability is related to the degree of preferential flow

2. Theoretical Background

2.1 Preferential flow

Infiltrating water can flow down the soil profile mainly following two mechanisms i.e. matrix flow and preferential flow. In the matrix /distributed /uniform flow water and solute move through the entire soil matrix pore network wetting the whole soil volume uniformly. In contrast, preferential /bypass flow describes a fast non-uniform movement of infiltrating water and solutes along preferred pathways that constitute a small portion of the total soil pore network, bypassing thus a fraction of the drier soil matrix (Hillel, 2004; Gerke, 2006). Macropores, live/decayed plant channels, soil fauna channels such as those from earthworms and termites, voids in naturally aggregated soils, cracks and fissures constitute pathways for the preferential flow of water through the unsaturated zone (Beven and Germann, 1982).

Preferential flow refers to all sorts of preferred pathway movements of water and solute in the soil. Specific flow types could be important based on the dominant preferential flow paths available. Allaire et al. (2009) classified four preferential flow types; *crack flow* (through cracks formed with soil drying), *burrow flow* (through channels created by soil fauna), *finger flow* (between different soil layers) and *lateral flow* (horizontal flow due to barriers). Macropore flow is a subgroup of preferential flow through continuous root and fauna channels, cracks and fissures in structured soils (Gerke, 2006). It represents, thus the burrow and crack flows.

Macropore flow initiation during infiltration depends on the initial soil moisture content, the intensity and amount of rainfall, the soil saturated hydraulic conductivity and the soil surface contributing area (Jarvis 2007, Beven and German, 1982; Weiler & Naef, 2003; Trojan and

Linden, 1992). Other influencing factors are slope (Zehe & Fluhler, 2001; Ohrstrom et al., 2002), other site factors and management (Jarvis 2007).

According to Jarvis (2007) wetter soils will usually lead to more preferential flow and saturation or near saturation of the soil surface layer is usually sufficient to generate preferential flow. Therefore, the importance of preferential flow will be considerable after saturation of the matrix pore network so that water fully flows to large macropores resulting in rapid non-uniform flow. Preferential flow tends to increase with rainfall intensity (Gjettermann et al., 1997; Alaoui et al., 2003) and duration since the soil water pressures attained during rainfall will be closer to saturation and may even reach saturation if the intensity is greater than the saturated conductivity of the soil (Jarvis, 2007).

2.2 Preferential flow quantification

Dye tracers are often used to visualize the infiltration pathways and quantify the degree of preferential flow (semi-quantitative assessment) in soils. This technique is relatively cheap, and provides further insights in the flow processes and spatial patterns (Kramers *et al*., 2009; Allaire et al., 2009). After visualization of dye stained profiles, the researcher is able to distinct those areas of the soil that participate in the flow from those that do not.

The food dye Brilliant Blue FCF (C.I.42090) has become a common dye tracer to stain the flow pathways in the vadose because it offers a good compromise between visibility, mobility, and toxicity (Flury & Flühler, 1994; German-Heins and Flury, 2000). Brilliant Blue FCF fronts are self-sharped and produce a strong color contrast with the soil material (German-Heins and Flury, 2000).

Despite increased research interest, quantification of preferential flow is still difficult (Allaire et al., 2009). The advancement in digital image analysis can help quantitative description of the dye infiltration patterns; however, there is no standard or generally accepted method to quantify the resulting dye patterns in the soil (Droogers et al., 1998).

Infiltration patterns produced by Brilliant Blue in the soil can potentially be analyzed by looking at the horizontal or vertical excavations or a combination of both. The techniques and the parameters used vary in accordance to the objective of the study. Possible analysis of the vertical dye pattern include the dye coverage profile in a soil (Flury and Flühler, 1994), the number of preferential flow paths per soil depth (Perillo et al., 1999), counting the number of stained pathways contributing to preferential flow (Gjettermann et al., 1997) and the ratio between area and perimeter of individual stained pores (Bouma et al., 1977), number among others. Weiler & Fluhler (2004) characterized the flow process by defining classes of stained pathway width (SPWs) and analyzing the degree of interaction between the horizontal and vertical profiles. Recently, Van Shaik (2009) used parameters (uniform front depth, preferential flow fraction and total stained area) to assess the dye infiltration pattern to compare spatial variability on the degree of preferential flow in different locations of a water-shed in semi-arid Spain.

2.3 Importance of preferential flow in the semi-arid tropics

In preferential flow, in contrast to matrix flow, only a small fraction of the soil volume participates in most of the flow. The existence of preferential flow can explain infiltration and drainage spatial variability, which affect ground water recharge and run off generation (Van Schaik, 2009). In macropore flow, only large macropores will conduct water, which in turn implies a faster effective pore velocity and shorter solute travel time (Jarvis, 2007). Rapid soil water drainage will lead to an enhanced ground water recharge (Van Schaik, 2009). In semi-arid tropics , where soil evaporation is so high, this fact is even more accentuated since the fast flow of water through macropores reduce water availability for evaporation in the top layers of the soil.

The soil surface characteristics may influence water movement in the soil especially in semi-arid tropics where surface crusting and sealing are common problems. In this sense, the presence of macropores connected to the soil surface can have large impacts on water infiltration (Beven and German, 1982). Casenave & Valentin (1992) analyzed factors influencing infiltration and run off for a large area by statistical analysis of data from 87 plots in semi-arid West Africa (mean annual rainfall less than 850mm). They found out that vegetation cover, faunal activity and intensity of surface crusting accounted for 84% of infiltration variability ratio as important surface conditions. Similarly, Perrolf and Sandstrom (1995) pointed out that soil texture and vegetation cover are determinants of infiltration in semi-arid Botswana and Tanzania. The change in soil surface condition could happen during the rainfall event when the aggregates collapse to form surface seal and crusting. The high rainfall intensity and long dry period in semi-arid tropics might induce surface crust formation (Sandstrom, 1995). These conditions could limit water flow into the macropores and increase surface run off. Trees can reduce soil crust formation and run off and increase infiltration (Bromley et al., 1997; Sarr et al., 2001; Ilstedt et al., 2007).

Preferential flow has received considerable attention in the subtropics in recent decades due to its impacts on water quality and groundwater recharge (Beven and Germann, 1982; Jarvis, 2007). However, little is known about preferential flow in the semi-arid tropics, where the biophysical environment is so different. For instance, the rain usually falls with higher intensities and is restricted to one season and followed by a long dry period.

3. Material and Methods

3.1. Study site

The study was conducted in the agroforestry parklands of Saponé, a village located 35 Km south of the capital Ouagadougou, in central Burkina Faso (12° 04’ 48” N, 1° 34’ 00” W). The altitude in the study site ranges between 310 and 325 m above sea level. The rainfall is unimodal with a rainy season extending from April to October. Mean annual precipitation is 787mm and the mean annual temperature 28^{o}c (Diréction de la Météorologie du Burkina Faso). According to the WRB (1988) classification, the major soil type of Saponé is Ferric Lixisols. The soil contains very low major plant nutrients: N=0.003%, Olsen extractable P=1.05ppm and exchangeable bases<2.5meq/gram (Jonsson, 1999).

The parklands of Saponé are dominated by Vitellaria paradoxa (Karité in French and Shea tree in English) and Parkia biglobosa (Néré in French and Locust bean in English) trees in the upper story, and maize, millet as associated crops. The tree density in the parklands ranges between 4 and 62 trees/ha.

3.2. Experimental design

Six transects were selected in the agroforestry parklands, characterized by different density distribution of the trees in the landscape. To accommodate this difference in tree density transects were divide into small (20-30m) and large openings (77-127m). Equal number of transects (three) were taken in each opening class. Transects were purposefully selected to include a tree with a termite nest and a tree without passing by the center of the opening among trees (figure 1). On average, the center of the three large opening transects are 48 meters away from the nearest tree. The center point of the small opening transects are 12 meters away from the nearest tree on average. Within each transect rain-fall simulations and Brilliant blue dye tracing experiments were conducted in three positions: *next to a tree*, *next to a tree with termite nest* and *center* (in the middle of the gap among trees) as shown in figure 1.

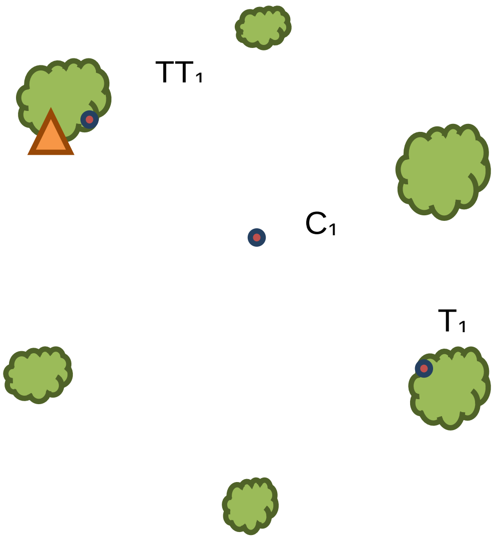

Figure1. Schematic diagram illustrating a transect with its three positions of rainfall simulation-dye tracing experiment. The symbols represent the positions (TT_1=trees with termite nest, T_1=tree and C_1= center)

3.2.1. Rainfall simulation and dye tracer experiment

A rainfall simulation was performed in each position of the transect, resulting in 18 rainfall simulations in total, during August and July 2011. A drip-type rainfall simulator modified from the one presented by Bowyer-Bower and Burt (1989), known as Amsterdam simulator, was used. The size of the rain simulation area (runoff collection plot) was 106 cm length by 55 cm width (Figure 2). The intensity of the simulated rainfall was 45 mm/hour, and the simulations lasted at least for one hour or until the infiltration reached steady state.

After the rainfall simulation, once the soil was saturated, 50 liters of water with food dye Brilliant Blue FCF (C.I.42090) at a concentration of 4g/L were added inside the runoff collection plot. Therefore, the initial moisture conditions were controlled, assuming that possible differences in stained patterns were not related to moisture content. Although Flury et al. (1994) concluded that initial soil moisture content had little or no significant influence on type of flow; others have found an influence on macropore flow initiation (Bouma, 1991, Zehe and Fluhler, 2001; Trojan and Linden, 1992).

The dye tracer Brilliant Blue FCF was used because it offers a good compromise between visibility, mobility and toxicity for visualizing flow pathways in the vadose zone (German-Heins and Flurry, 2000).The ponded water was let to infiltrate into the soil. After one hour, a pit was dug next to the tracer experiment plot. The soil pit was 70 cm wide and 2 meters long in order to accommodate the device consisting of the camera holding platform and a 500 x 500 mm frame-connected to it through 3 beams. The device was built in such a way that the focal point of the camera was at a distance of 1.5 m from the frame and centered into it. The camera holding platform, on the other side, was perpendicular to the frame, assuring the orthogonality of the pictures.

The profiles were prepared to keep a vertical position and leveled surface, avoiding smearing. A graded frame with inner dimensions of the 500 x 500 mm was aligned in the vertical profile, leaving 25 mm away from the edges of the dyed profile in each side to reduce the border effect. The soil profiles were photographed with a Nikon D-3100 digital camera using a focal length of 35 mm. The resulting pictures had a resolution of 4608 by 3072 pixels. Pictures were taken under day light condition beneath iron sheet to provide diffuse light and minimize direct radiation, thus reducing the shadow effect in images further away to the center. Six vertical soil profile pictures and five horizontal sections were photographed in each position of the transect. The spacing between the vertical sections was 10 cm from each other. The 2nd, 3rd, 4th and 5th vertical profiles per position were used for this study due to the time constraints of the thesis work. Each vertical profile has 500 mm depth by 500 mm width. The vertical and horizontal profiles in one position are shown in figure 2, though the horizontal profiles from 7-11 were not used in this study.

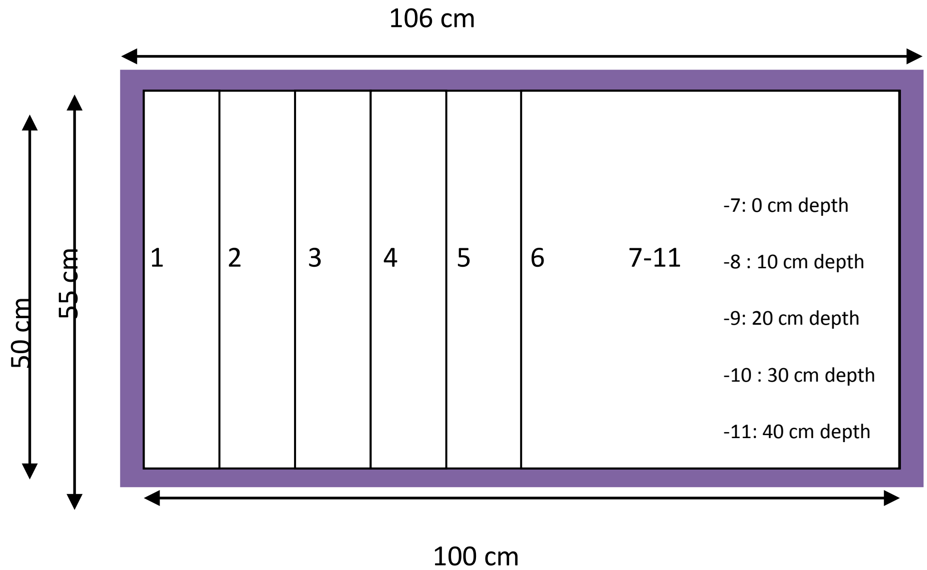

Figure 2. Schematic lay out of the vertical and horizontal soil profiles in one position. Numbers from 1 to 6 indicates the vertical soil profiles taken 10 cm apart from each other and 7-11 represent horizontal soil profile samples taken in opposite direction to the vertical profiles starting from the surface to the lower depth (not represented by lines).

3.3. Image processing and classification

Images were processed and classified with a set of procedures using ERDAS imagine 9.3. The major steps followed are presented below.

3.3.1. Geometric correction

Geometric correction is a rectification of the distorted image using mathematical transformation. The common geometric distortion in the soil profiles are attributed to the optical deviations in the lens of the camera, abnormalities in the view angle of the soil plane and soil section roughness (Weiler, 2001).

An approximate pixel size was determined by knowing that the frame was 500 x 500 mm, and taking an average of the number of pixels in columns x rows for all images, excluding those that were outliers. For example, the average size in pixel columns and rows (excluding the 4 outlier images) was 2427 x 2429. For the sake of evenness, a 2428 x 2428 pixel area was equated to the 500 x 500 mm frame. Therefore the pixel scale was 50/2428 = 0.20593335 mm per pixel.

The Tl7tree 3 image was chosen as a reference image for geometric correction of other images because it was the image that was closest in size to the average among all the images (2427 x 2426). Eight ground control points (GCPs), four taken at the corner of the frame and the other four in the midpoint were used from the image being corrected to the reference image in respective order.

This established a mathematical relationship between the locations of the GCPs points in the image being corrected and the ones in the reference image. A 2^{nd} order polynomial equation was selected because applying higher order polynomial transformation would introduce larger error to the center of the image away from the GCPS as the GCPs were selected in the frame (Weiler and Fluhler, 2004). The bilinear interpolation resampling method, which assigns the average values of the four nearest pixels to the new pixel location in the corrected image, was used. The rectified image was displayed on top of the reference image to evaluate the correction process to the required level. The position of the frame of the corrected image should fit to the reference image when corrected properly. Finally, the geometrically rectified image area inside the frame was clipped and used for further analysis. This clipped image was 2428 by 2428 pixels in size.

3.3.2 Image Classification and analysis

Image classification is the process that categorizes the image pixels into discrete thematic classes using statistical decision rules. The images were classified into blue dye and soil classes using supervised classification. The blue dye class was defined from the training areas, visually chosen by the analyst with spectral signature ranges from dark blue to light greenish pixels. Small uniform groups of pixels for each spectral signature were digitized and the colors of all the training areas for blue dye class were grouped into a single ''blue'' class in supervised classification. The same method was used for soil class with spectral signatures from dark red to gray.

The supervised classification method is appropriate when the analyst has sufficient ground information or knowledge to assign/identify sets of pixels in the image that belong to a certain class. The spectral signatures of the image that represent each of the information classes (blue dye and soil) were digitized and used as examples or " training areas" for the classification. These training areas are used as examples by the computer program to indicate what the different classes of the image look like spectrally. The computer program uses maximum likelihood to assign all pixels in the image into classes according to their spectral signature. Generally, five training areas were selected carefully to include all spectral signatures in each class though in some complex images extra training areas were considered. Then classification was performed with training areas and using maximum likelihood rule. Maximum Likelihood rule is a process in which the probability of an unclassified pixel belonging to a user-defined class is calculated and unclassified pixels are assigned “the most likely” class.

It is worthwhile to evaluate the classified image in relation to the unclassified one in each soil profile after classification. The classification was assessed in detail by displaying the classified image on top of the unclassified image to identify potential misclassified areas.

In addition, the range of training area signatures was observed in feature space. For each image, three feature space images (two pairs) were created from the combination of layers (Green, Blue and Red). One feature image was displayed and the ellipses with the labels for all the training area signatures were plotted (figure 3). If the training area signatures of the different classes overlap, this means that a pixel with similar signature could be classified as either of the two classes. When there is some overlap between the training areas, the overlapping training areas were removed and the image was classified again using a new set of training areas.

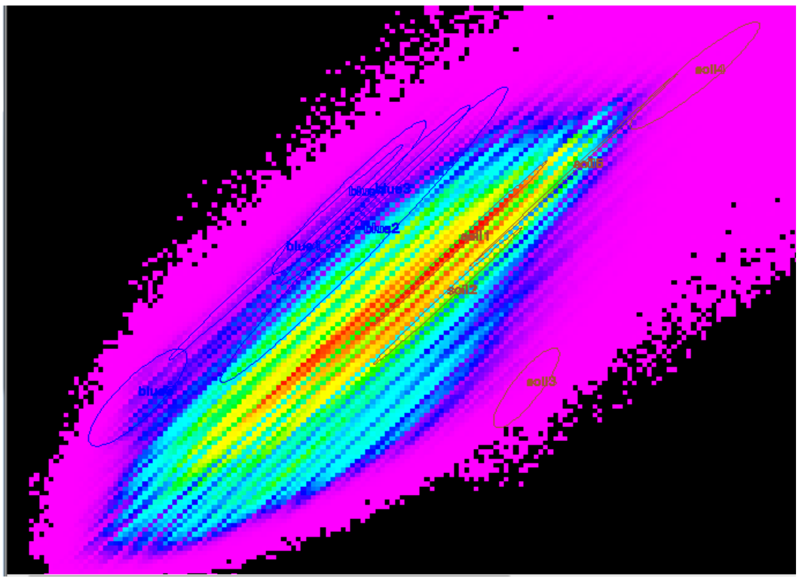

Figure 3. This image shows evaluation of spectral signature ranges of training areas in the feature space image. The ellipses in the blue color represent the training areas of the blue

dye class and the ellipses in the red color are those for the soil class. In this example, no overlap between the blue dye and the soil classes and therefore there was no need to make new classification.

Once the classification was finished, the classified image was recoded to blue and soil classes. Roots and dark big macropores were manually digitized and classified into separate classes (fig.4). Roots were divided into two classes, the ones that grow perpendicularly to the soil profile and those that grow in other directions. Big macropores in the image (root channels, fauna galleries and cavities) could include black-dark areas which were initially classified as blue dye in the supervised classification (fig.4). However, since those areas were so dark, the classification couldn't be trusted, meaning that the blue dye might have passed through partly or not reached there. These areas larger than 2 cm diameter in the longest direction were manually delineated and categorized as big macropores. Those macropores that were clearly dyed in blue were not considered in this class. Finally, to get rid of the pixelly effect of the classified image (where the appearance of small number of pixels for a class create a noisy result), smoothing or generalization with a minimum number of 10 pixels in a group was executed.

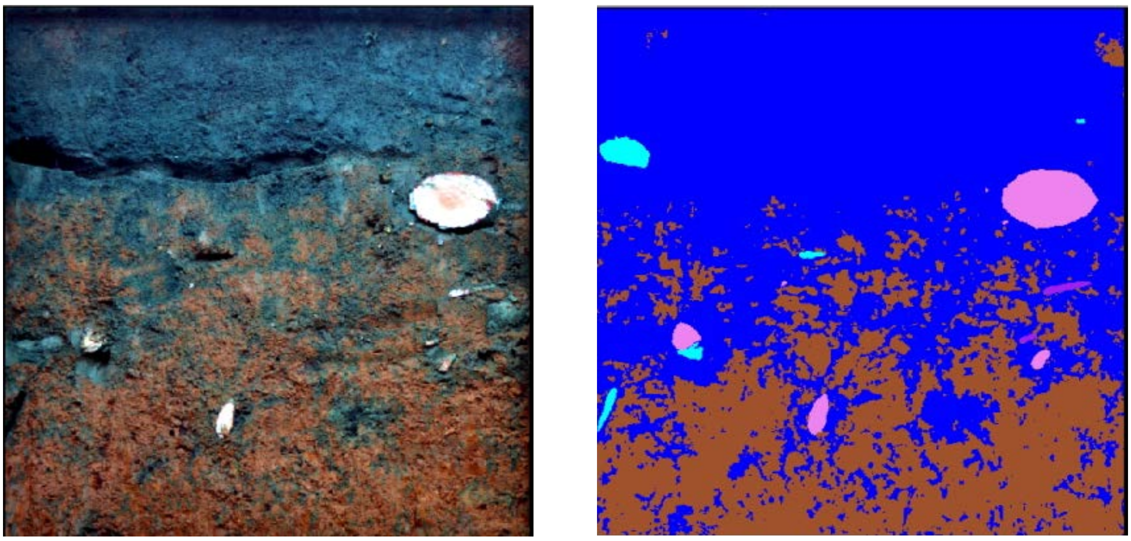

Figure 4. This figure shows an example of the original and the corresponding classified image from left to right, respectively. Each class in the classified image is represented by different colors; (blue=dye stained, brown=soil, violet=roots perpendicular to the profile, purple=roots in other directions, cyan/greenish=big macropores).

The analysis of the classified images was performed in ArcMap 10 using the Tabulated area tool from the package Spatial Analyst. The tabulated area tool calculates the area covered by each class within different zones in the picture which are defined by a polygon shapefile. The depth profiles was divided into 100 segments of equal depth of 5 mm. The different soil classes was translated to a polygon shape file resulting in a table with the area of each soil class for each 5 mm depth. The resulting data, a table including the 100 zones and the area of each class present in each zone was exported to Excel, where all the calculations were computed. Depths of rectangular polygons were specified by taking the midpoints of the height of each polygon in relation to the soil surface as a reference (zero-value) downwards. This allowed possibility for detailed investigation in proportion of blue, soil, perpendicular roots (or other directions), and big macropores per polygon, between polygons on the same image downwards in the soil profile and also to extract parameters or indices to examine the treatment effect on preferential flow.

3.4. Parameter definition to assess preferential flow

In this study, parameters used by van Schaik (2009) together with some new suggestions from the dye infiltration pattern were used to illustrate effect of trees and termite nests on the degree of preferential flow from rain simulation-dye tracer infiltration experiment. The list of parameters used, its definition and a brief description are presented as follows.

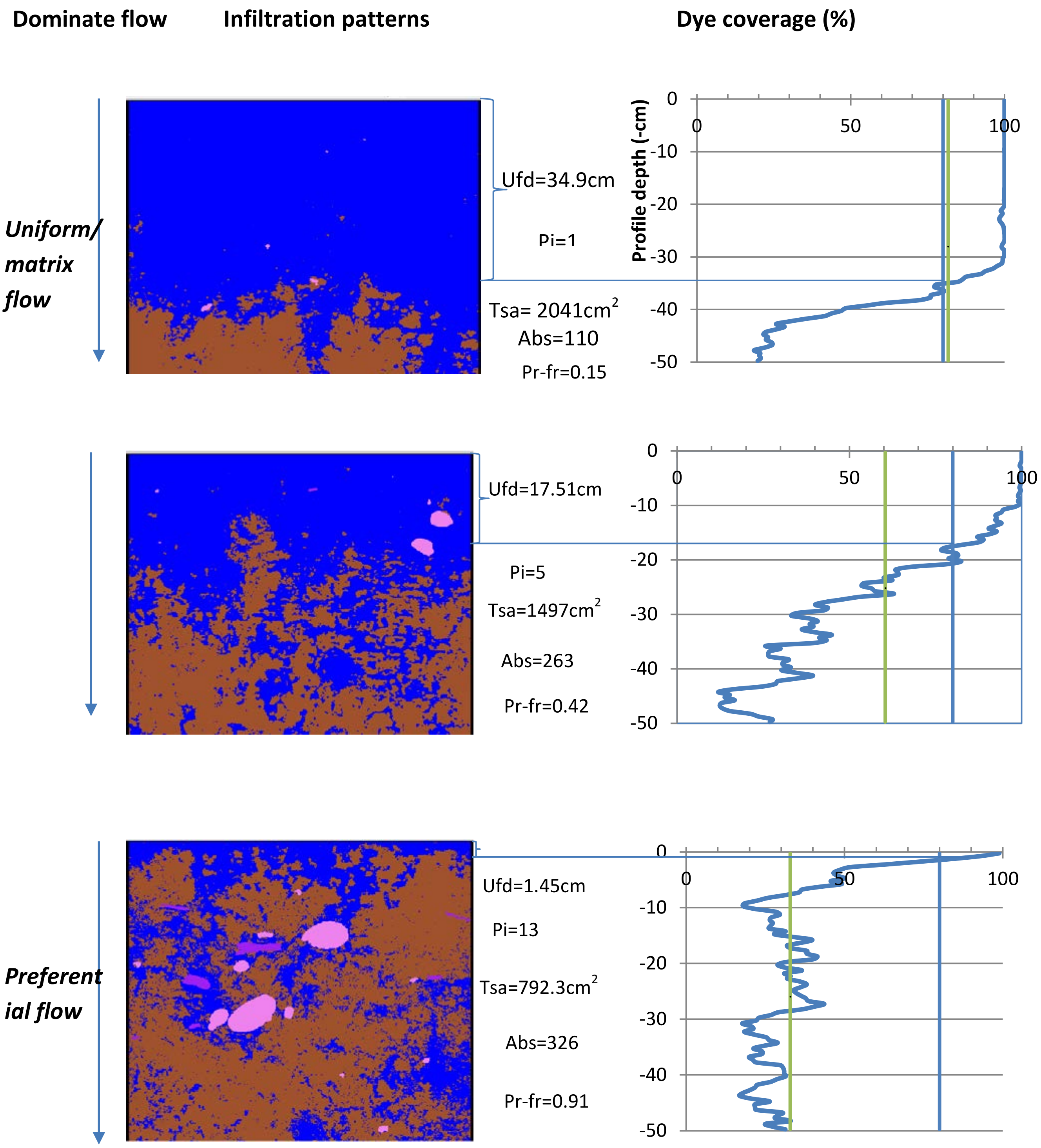

Figure 5. This figure shows how parameters of preferential flow were derived from dye infiltration patterns. The images on the left side represent a gradient of stained patterns from uniform/matrix dominated flow to preferential dominated flow. The different colors represent the classes (blue=dye stained, brown=soil, violet=roots perpendicular to the profile, purple=roots in other direction, cyan=big macropores). The graphs in the right side are the dye coverage –profiles corresponding to the left images, where dye coverage (%) is plotted against soil profile depth. Ufd =uniform front depth (cm), Pi=peak index, Tsa =total stained area (cm^2), Abs= Absolute slope sum. The blue line depicts threshold of 80% dye coverage, while the green line represents the average dye cover in the profile.

Uniform front depth (UFD): is the depth at which the homogeneous infiltration pattern decreases noticeably down the profile in reference to the soil surface. It represents the part of the soil profile where the infiltration process is dominated by matrix flow. Uniform front depth in this study is defined as the depth at which a dye coverage below 80% is first attained (represented by the line marking the 80% threshold in figure 5) (van Schaik 2009). To get the exact depth where dye coverage is 80%, interpolation was used. If the soil has a matrix diffuse flow, water moves uniformly through its entire volume. Hence, the uniform front depth will be higher (figure 5).

Preferential flow fraction (pr-fr): is the portion of the total infiltration that flows through the preferential flow paths. It is calculated as:

$$\textit{Preferential flow fraction (pr-fr)} = 1 - \frac{uniform\ front\ depth(cm) * width\ of\ the\ profile(cm)}{total\ stained\ area(cm^2)}$$

In our case the width of the profile is 500 mm

Absolute slope sum (Abs): is the sum of the difference in absolute slopes of the dye coverage curve between consecutive 5 mm sections beginning from the soil surface down to 500 mm depth. The sum of absolute values of slope of the blue dye coverage profile curve per unit increase in the soil depth will be substantial in soils dominated by preferential (heterogeneous) flow as compared to those dominated by uniform flow (figure 5). As it can be seen in figure 5, in the first dye coverage profile, the dye coverage was nearly constant till a depth of 300 mm, meaning that the slope was close to zero. This corresponds to the soil fraction dominated by uniform matrix flow. Below 300 mm depth slope increases, corresponding to the preferential flow dominated section. However, in the lower two graphs slope per unit profile depth is higher and more variable.

Total stained area (Tsa). It is the total blue stained pixel area of an image. Profiles with high preferential flow will have lower stained area than those with more soil matrix flow because in the first case water moves through preferential pathways bypassing thus the soil matrix and in the second case it flows through the entire volume of the soil matrix.

Dye coverage (%): is the percentage ratio of the dye stained area to the sum of dye stained and soil area in each image**.**

$$\text{Dye coverage\%} = \frac{\text{blue stained area(cm2)}}{\text{blue +soil staiend areas(cm2)}} * 100$$

This formula was also used to calculate the dye coverage (%) for each rectangular polygon per profile, which was the basis to plot the dye coverage curves like the ones showed in figure 5.

Peak index (Pi): It is a parameter derived from the average dye coverage percentage per profile. The average dye coverage percentage of the 100 rectangular areas per profile was calculated. This average value was plotted on the dye coverage percentage profile (figure 5). Then, the number of times that the dye coverage curve crossed the average line was counted. This number corresponds to the peak index. In a matrix dominated flow, the first dye coverage profile in figure 5, the peak index is low, while it increases downwards with preferential flow.

Standard Deviation of blue dye percentage (sum): it is the sum of the standard deviation of the blue dye coverage percent from the 2nd, 3rd, 4th and 5th soil profiles computed per rectangular polygon per position. When the dye coverage percent of the four vertical profiles are plotted with depth on the same graph, one can see the variation between each other along the profile. The same comparison can be made between graphs of different positions. This is the basis to defined standard deviation as index to grasp the variation between positions.

3.5 Statistics

The mean value for each of the parameters of preferential flow was calculated from the four vertical soil profiles used per position. For big macropores, the fraction of big macropore areas in relation to the total stained area per soil profile was calculated first and this proportion of the four vertical soil profiles were weighted to get the proportion of big macropore per position. Similarly, the root area (for both perpendicular and other direction) proportion to the profile area was computed.

The effect of treatments on the degree of preferential flow was tested using ANOVA-General Linear Model based on a mixed hierarchical (nested) model in Minitab 16 (Minitab 16 Inc., USA). Two fixed treatments were considered in the model: opening size (large /small opening) and position (tree, opening center and tree with termite nest); the different transects, or blocks, were taken as a random treatment. If the block treatment had not a significant effect it was removed from the model in the next step, leading thus to a non-mixed model. In order to test for the differences in the degree of preferential flow between large and small openings, the same model was used but the position treatment was fixed (opening center). The means were separated by Tukey's pair-wise comparisons with the 95% confidence interval. Linear regression was used to test the degree of preferential flow with distance from the nearest tree and tree with termite nest using preferential flow parameters. In every analysis, fulfillment of normality requirements and need for data transformation was inspected. The following significance levels were used.

Table 1. P-value significance levels to the treatment effect.

Parameters	p-value	Level of significance
Absolute slope	0.011	*
Uniform front depth	0.012	*
Total stained area	0.042	*
Big macropores	0.017	*
Total roots	0.010	*
Peak index	0.055	(¤)
Preferential flow fraction	0.064	(¤)
Total dye coverage	0.062	(¤)
SD index	0.214	(✠)

$P<0.001$; statistically most significant (***)

$0.001<P<0.01$; statistically more significant (**)

$0.01<P<0.05$; statistically significant (*)

$0.05<P<0.1$; close to significance (¤)

$P>0.1$; not significant (✠)

NB: term significant and statistical significant will be used to refer $0.01\leq P<0.05$ throughout the text.

4. Results

4.1 Assessment of treatment effect with preferential flow parameters

The analysis showed that the effect of the position treatment (tree/tree and termite nest/opening) was significant for some of the preferential flow parameters and very close to significance for others (table 2). The parameters with significant effect on treatments are stated in the following section.

Table 2. Results of the ANOVA - GLM analysis for the effect of position treatments on preferential flow and the corresponding p-value at 95% confidence interval.

Parameters/indices	p-value
Absolute slope	0,011 *
Uniform front depth	0,012 *
Total stained area	0,042 *
Big macropores	0,017 *
Total roots	0,010 *
Preferential flow fraction	0,064 (¤)
Peak index	0,055 (¤)
Total dye coverage	0,062 (¤)
Steady state inflitrability	0.082(¤)
SD index	0,214 (✠)

* Statistically significant

(¤) close significance

(✠) not significant

The absolute slope sum values in trees with termite nest and without were significantly higher than in the openings while trees and tree with termite nest did not have significantly different absolute slope (table 3). As revealed in figure 5, when water flow in the soil profile is dominated by preferential flow, the absolute slope value is high and vice versa in matrix flow.

Table 3. Results of ANOVA-GLM analysis on preferential parameters and Tukey's method mean grouping for parameters at 95% confidence interval. Means with the same later are not significantly different.

Positions	Number	Mean parameter value and its grouping				
		Absolute slope	Uniform front depth	Total stained area	Total big macropores	Total roots
Trees	6	183.5^{a}	18.1^{ab}	1452^{ab}	0.34^{ab}	1.86^{ab}
Tree with termite	6	170.4^{a}	7.4^{b}	1112^{b}	0.67^{a}	3.28^{a}
Open(center)	6	125^{b}	26.5^{a}	1763^{a}	0.11^{b}	0.30^{b}

The uniform front depth in trees with termite nest was significantly lower than in the openings. Trees with termite nests have twice and three times less mean uniform front depth than that of trees and the openings respectively. As can be seen in table 3, trees were not statistically different from tree with termite nest and the openings though the mean uniform front depth difference was high. The uniform front depth and the total stained area are linearly related to each other (appendix 1) and the two treatments revealed the same treatment effect (table 3). Water flowing through preferential flow pathways stains less volume of soil area in comparison to the water flowing through the entire matrix, the total stained area in tree with termite was lower than in the openings (table 3). The total stained area in trees was not significantly different from the tree with termite nest and the openings.

The big macropores and total roots were significantly higher in trees with termite nest than in the openings. The average fraction of big macropore area per position in trees with termite nest was twice higher than in trees with out and six times that of the openings (table 3). Trees did not significantly different from the tree with termite nests and openings. Big macropores and roots decreased from next to tree with termites, then trees without to the openings.

The steady state inflitrability was not significantly different in position treatments, opening size and there was no relationship between absolute slope sum(fig.12), more sensitive parameter for degree of preferential flow.

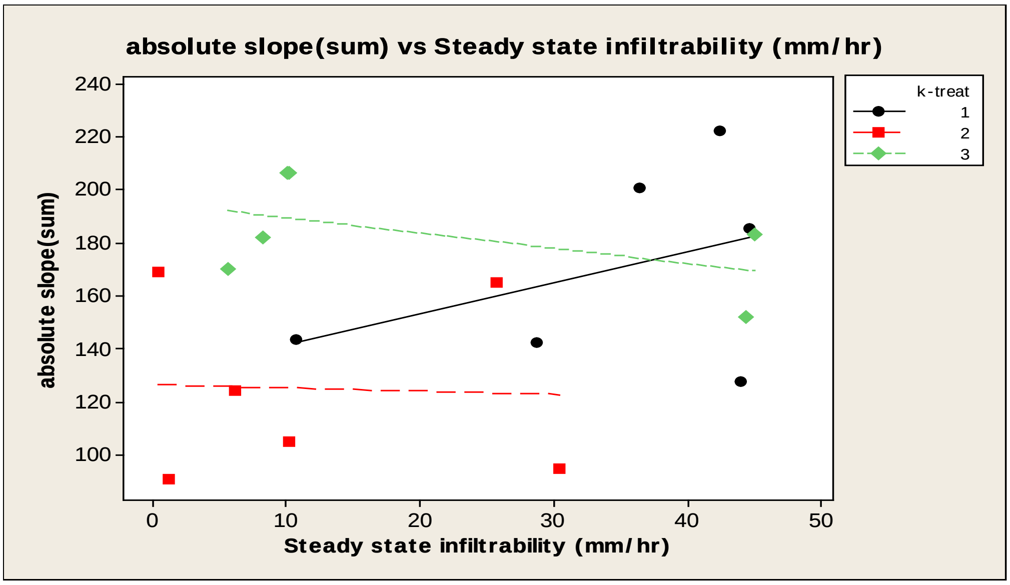

Figure 6. The relationship of absolute slope sum against steady state inflitrability (mm/hr) in position (tree/tree with termite /open) treatments

4.1.2. Interpretation of the parameter estimates to preferential flow

Preferential flow has a direct relationship with absolute slope sum and an inverse one with uniform front depth and total stained area parameters. If water flows through preferential flow paths, constituting small fraction of the soil, the uniform front depth and the total stained area decreases whereas the absolute slope increases (table 3). Absolute slope measures the change in length of the dye coverage curve per 5 mm soil section commencing from the soil surface to 500 mm depth and the value will be higher number when the water flows preferentially (table 3). Uniform front depth and total stained area were significantly lower in tree with termite nest than in the openings (Table 3) which indicates the relative importance of macropore flow in tree with termite nests in channeling water. The absolute slope was higher in tree with termite nest and without than in the openings (table 3). This all entails that the degree of preferential flow in tree with termite nests was higher as compared to the openings.

4.2. Effect of opening size

The effect of opening size was significant only for one of the preferential flow parameter (table 4). The prevalence of preferential flow in small openings was significantly higher than in large openings assessed by the absolute slope parameter (fig.7). The mean absolute slope of the large openings was 42% less than in the small openings.

Table 4. Results of the ANOVA- GLM analysis on the preferential flow parameters to measure the effect of opening size on preferential flow and the corresponding p-value at 95% confidence interval.

Parameters/indices	p-value
Absolute slope	0,036*
Uniform front depth	0,065(¤)
Preferential flow fraction	0,293
Total roots	0,659
Big macropores	0,685
SD index	0,674
Peak index	0,588
Total stained area	0,120
Total dye coverage	0,134
Steady state inflitrability	0.809

* Statistically significant

(¤) close to significance

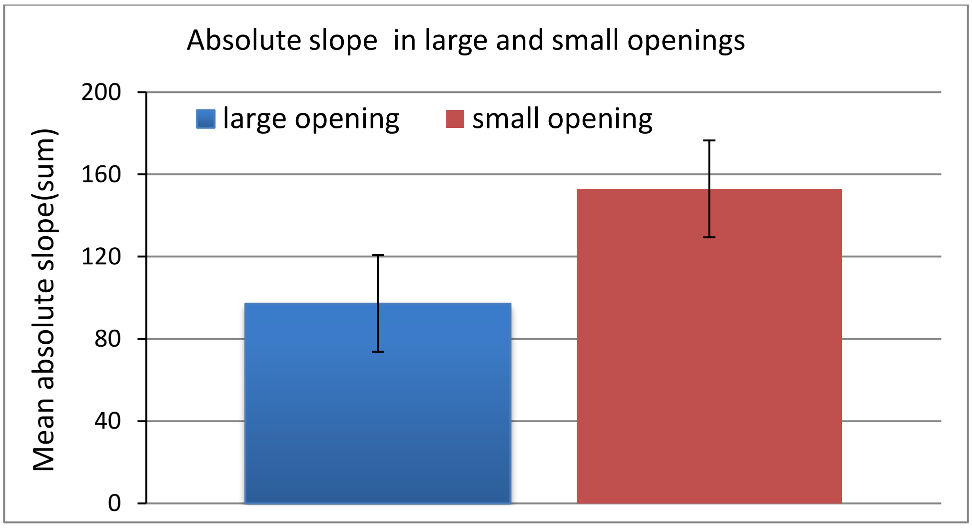

Figure 7. The effect of opening size measured with absolute slope in large and small openings and the error bar indicates SE mean differences.

The uniform front depth was close to significance (*p-value=0.065)* with the opening size. The uniform front depth in large openings was higher than in small openings. Small openings have more preferential flow than the large openings (fig. 7 & 8) because of the influence by the nearby trees.

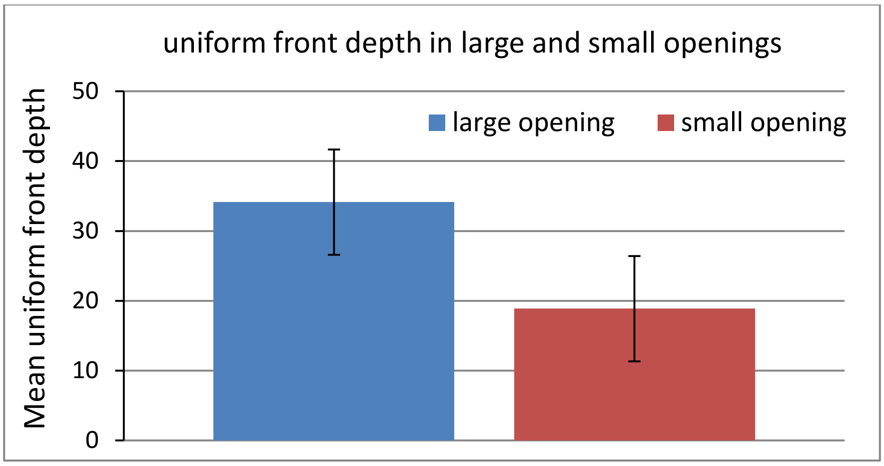

Figure 8. Opening size effect assessed by uniform front depth in large and small openings with error bar represented by SE mean differences.

4.3. Preferential flow with distance to nearest tree

4.3.1 Absolute slope (sum)

The preferential flow, assessed by the absolute slope parameter, decreased most significantly (p-value <0.0001) with an increase in distance from trees. From figure 9, absolute slope close to trees have two cluster groups i.e. above and below the trend line. All the observations above the trend line were positions close to the large size trees in diameter. Small openings have significantly higher preferential flow than the large openings with absolute slope sum parameter (table 4 & figure 9. This signifies that degree of preferential flow decreased with distance away from the closest tree and termite nest.

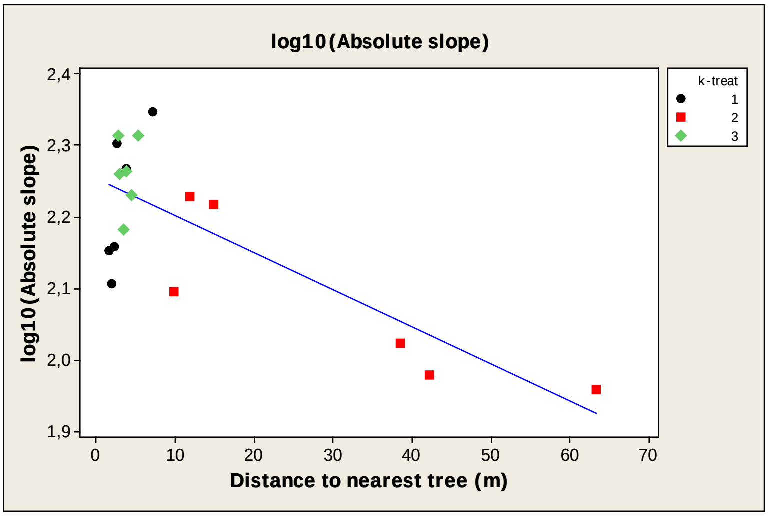

Figure 9. Logarithmic absolute slope plotted against distance to the nearest tree ($R^2 = 59.8\%$, p-value<0.000). The positions represent; 1= next to tree, 2= openings and 3= termites.

4.3.2 Uniform front depth

Preferential flow, assessed by uniform front depth, decreased significantly (p-value = 0.010) with increase in distance from the nearest tree and termite nest to the openings. The range of the uniform front depth in positions close to trees was wide and clustered in two groups (figure 10). Two-third of the observation had uniform front depth greater than 20 cm and above for the trees with termite nest. The two lowest uniform front depths (0.8 cm and 4.15 cm) correspond to positions close to trees with DBH of 74 cm and 52.5 cm respectively.

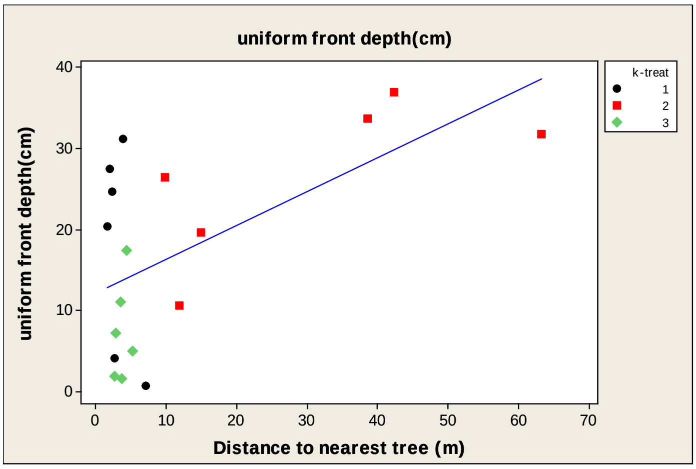

Figure 10. Uniform front depth plotted against distance to the nearest tree (R^2 = 34.6%, p-value = 0.010). The positions represent; 1= next to tree, 2= openings and 3= tree with termites.

4.3.3. Total stained area

The total stained area increased significantly (p=0.020) with distance away from tree with termite nest and without to the openings. Half of the observations (three) close to trees have equivalent total stained area to that of the large openings (fig.11). The two lowest total stained areas close to tree were positions stated in the uniform front depth that might have been influenced by tree size and land management.

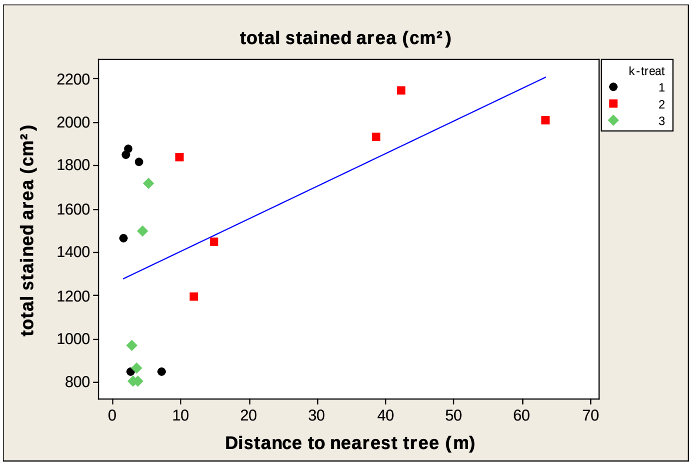

Figure 11. Total stained area plotted against distance to the nearest tree (R^2 = 29.6, p-value = 0.020). The positions/treatments represent; 1= next to tree, 2= openings and 3= termites.

4.3.4 Steady state inflitrability (mm/hr)

The steady state inflitrability was not significant with distance from the nearest tree with termite nest and without to the openings(fig.12).

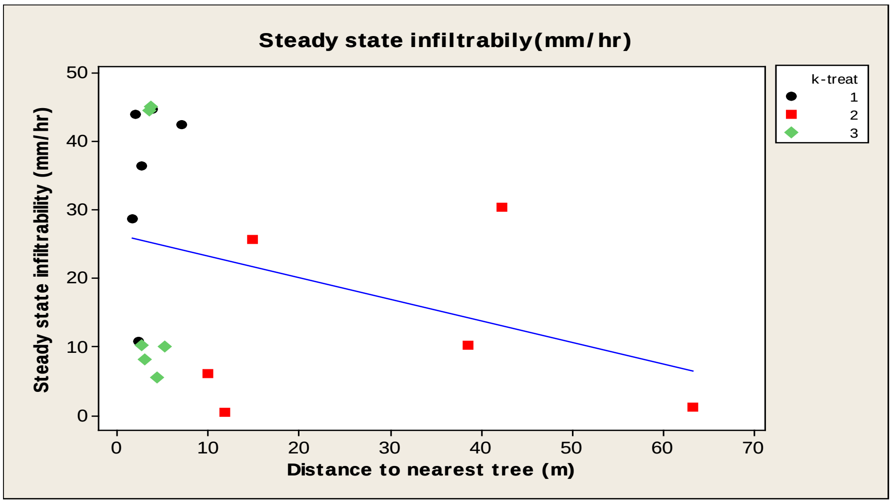

Figure 12. Steady state inflitrability (mm/hr) with distance to the nearest tree (R^2=10.4%, p-value=0.193)

5. Discussion

5.1 Parameters to assess dye infiltration pattern

Different researchers used preferential flow parameters to infer dye infiltration patterns. Van Schaik (2009) used preferential flow parameters derived from infiltration patterns and high predictive site characteristics to indicate area of different degree of preferential flow in semi-arid watershed of Spain. Kulli et al. (2010) divided the vertical dye infiltration patterns into similar stained horizontal layers based on width distribution of stained areas. The similar layers from all samples were partitioned into groups of layers with similar patterns by hierarchal clustering and classified zones of homogenous flow and preferential flow. It was pointed out that dye coverage and width of the stained structures were good indicative factors of different clusters. Preferential flow parameters are used to deduce difference in land use. Cheng et al. (2010) found that shrub land and farm land have more preferential flow in the top soil layers than forested soils with the reverse in the deeper layers in southwest china. Shougrakpam et al. (2010) used dye coverage (%) per soil depth density function, stained pathway width, maximum and average size of macropores, and number of active macropres to analyze the effect of different land use (undisturbed forest, cultivated paddy fields, forest lands abandoned after Jhum cultivation, pineapple and banana plots) on the macro porosity in India. They found that higher macroporosity in undisturbed forest than the paddy field due hard pan formation in paddy field and tillage. Despite related parameters have been used to assess infiltration patterns; literature is limited specific to this study.

5.2. Parameters and preferential flow

Assessment with parameters showed that trees and termite nests influence preferential flow. The correlation between some parameters was relatively strong to each other (appendix 1). Since the definition most of the parameters were mainly based on dye coverage curve, there is high potential correlation among them. For example, the uniform front and preferential flow fraction have a mathematical relationship and therefore some kind of correlation is expected. The correlation problem has been reported by Van Schaik (2009) stating that parameters are the function of the combined effect of many factors which are related to each other.

Among the significant parameters, the total stained area and the uniform front depth, big macropores and roots have strong correlation to each other (appendix 1). The predictive values of these parameters for preferential flow gave more or less similar results (table 3) despite based on different information. Using one of the parameter from the pair can give the same result.

The absolute slope sum was found to be more sensitive to the effect of trees and termite nest on preferential flow than other parameters. Both the position (tree/tree with termite/opening) and the opening size (large and small) treatments were found significantly different with absolute slope. This may perhaps be related to its measure of change in length of the dye coverage curve between consecutive 5 cm soil sections for the whole soil profile in contrast to other parameters such as uniform front depth which simply divide each soil profile into two sections of uniform front depth and preferential flow fraction, without describing the degree of variability of the dye coverage curve within two sections. We can have two profiles where 80% dye coverage is reached at the same depth (uniform front) where the dye pattern downwards is completely different. This difference is not taken into account by parameters such as uniform front depth while absolute slope does.

On top of this, it has been observed that the soil profile has two distinct soil horizons identified by different colors in some profile pictures. The difference was obvious within a soil profile or between positions. The depth and the infiltration pattern in those profiles were different. Absolute slope can include this variation better than the other parameters.

Parameters that take into account the whole soil profile may perform better to predict the position treatment effect.

5.3. Effect of tree size on preferential flow

The degree of preferential flow in trees did not statistically differ from trees with termite nest and openings for any of the parameters used with exception of absolute slope. This may possibly be ascribed to the tree size effect. Figure 13, shows that the tree size has a tendency to influence the degree of preferential flow, assessed by the absolute slope parameter, in positions next to a tree, but there is no relationship for trees with termite nest. The high level of explained variation (R^2=60.5%) and close to significance relationship (p=0.068) for trees is a sign of increase in degree of preferential flow with tree size regardless of different land management in transects. This is in agreement with findings from Devitt & Smith (2002) that larger shrubs and root sizes increase preferential flow.

Gnankambary et al. (2008) also found low litter quality (N, C) to support soil organisms and slow decomposition under the canopy of Vitellaria paradoxa. The tree could need to reach a big size to provide sufficient litter to support enough soil organisms to have a considerable effect on preferential flow. The effect of tree on preferential flow becomes important when the diameter at breast height is greater than 50 cm (fig.15). The tree with DBH of 49.5 cm was in a ploughed transect and also had smaller crown diameter(2 m) in relation to its DBH resulting in the lowest absolute slope value among trees which perhaps influenced the trend line in figure 13.

The effect of macropore channels from termite nest in positions close to a tree with termite nest might be compensated with more macropores induced from large trees. Hence, larger trees tend to have similar effect as trees with termite nests on macropore flow and degree of preferential flow. Separate analysis based on tree size possibly will give a clear notion of the effect of trees on preferential flow.

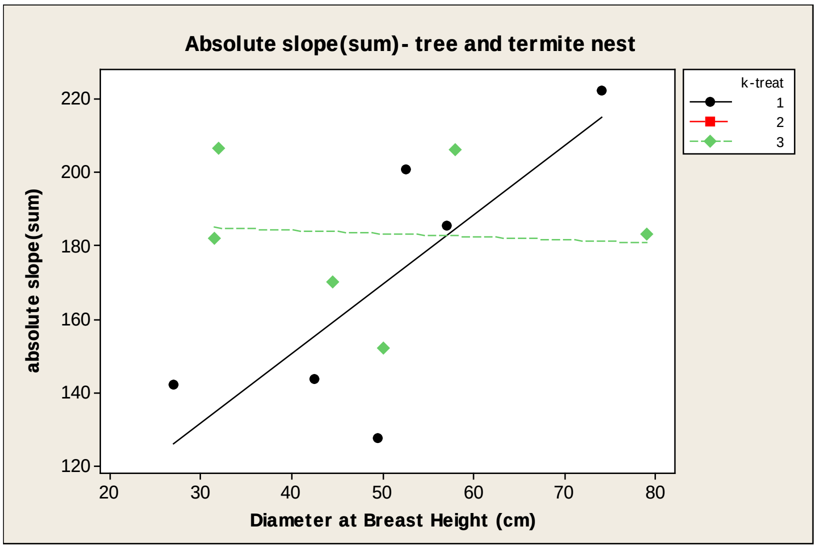

Figure 13. The relationship between Absolute slope and diameter at breast height (DBH) for positions next to tree and tree with termite nests (Tree: R^2 = 60, 5%, p-value=0,068; Tree with termite nest: R^2= 0, 6%, p-value =0.889). Treatments represent; 1=next to tree, 3= tree with termite

5.4. Preferential flow in different positions

Preferential flow decreased with an increase in distance from tree with termite nests and without to the openings. This result is in line with the finding of Joelsson (2012) for a decrease in steady state inflitrability from tree with termite nest to the openings. Preferential flow in trees with termite nests and trees without were mainly due to macropore flow. The amount of big macropores and the roots, preferential flow pathways, were significantly higher in trees with termite nest in relation to the openings. Relatively higher proportion of roots in positions close to tree with termite nests than trees without could be associated to the higher nutrient content close to termite nests (Jouquet et al., 2011; Traoré et al., 2008; Fall et al., 2001). This is consistent with increase in preferential flow along roots and root prompted macropores (Mitchell et al., 1995; Breman and Kessler, 1995; van Schaik, 2009) and through soil faunal channels such as termite nests (Léonard, 2004).

Preferential flow in trees without termite nests was significantly higher than the openings with absolute slope sum parameter and not statistically different with other parameters. This is in contrary to the literature that trees improve preferential flow (Beven and Germann, 1982; Belsky et al., 1989; Salvador et al., 2011; van Schaik et al., 2009; Colloff et al., 2010).

Joelsson (2012) also showed no statistical difference macro porosity at 25-30 cm depth from trees without termites nests with increase in distance to the opening. This is supported by the findings of Sanou et al. (2010) that soil inflitrability under the tree and the open field was the same due to tillage and animal trampling effect other tree species. Tree canopies usually serve as shelter for human and animals in Burkina Faso which could make more compaction (Sanou et al., 2010, Savadogo et al., 2007). This compaction can also vary in time and between trees.

Tillage has been reported to have different effects on infiltration. It can decrease infiltration through blocking macropores created by soil fauna and root growth (Ouattara et al.,2007; Eldridge & Freudenberger, 2005) and can increase it by breaking the soil crust and creating new macropores (Kribaa et al., 2005; Cameira et al.,2003). This can introduce variation in value of preferential flow parameters.

The parameter value ranges or SE of the means in trees with termite nests and without are wider for absolute slope, uniform front depth and total stained area (fig.9, 10 &11). This high variability under trees and trees with termite nests could explain the usual lower R^2- value for the relationship between preferential flow and distance from closest tree. Moreover, trees without termite nest have higher variability in the parameter values than in trees with termite nests which make it to behave the same effect as both to tree with termite nest and openings.

The effect of opening size was significant with absolute slope and close to significance with uniform front depth. Besides, the degree of preferential flow from tree with termite nests and without had decreased significantly to the openings. This highlights the positive effect of closer trees (small openings) on the degree of preferential flow.

In all parameter estimates, trees and trees with termite nests did not have significantly different preferential flow. This is consistent with Joelsson (2012) finding of no significant difference in steady state inflitrability between trees with termites and without.

The combined effect of tillage, compaction, tree size (fig.12) and small sample size could have contributed to inconsistence of the trees without termite nest effect on preferential flow compared to the openings. On top of this, the design of the experiment may have the influence on the effect of trees without termite nest in relation to openings. If the design was only with trees and openings, the trees effect would be significant than the openings.

Water inflitrability estimated by steady state inflitrability was not significantly related to the degree of preferential flow (fig.6, 12 and table 2). This is contrary to the positive effect of trees in agroforestry systems to infiltration (Ilstedt et al., 2007; Colloff et al., 2010,). Hanson (2006) also found that the infiltration capacity under trees and with compost was higher than the openings. The infiltration capacity measurement was in between and under shea butter and Faidherbia albida before and after tilling, with and without compost in semi-arid Burkina Faso. High rainfall intensity coupled with tendency of soils in semi-arid tropics to form soil crust (Perrolf & Sandstrom, 1995; Casenave & Valentin, 1992) where soil pores could be closed may result in insignificant steady state inflitrability between treatments.

5.5. Difference in transects and positions

The transects have different land management history and crop type. Two of the three small opening transects were fallowed for three years and the other for one year. Of the three large opening transects, two were ploughed and the other had been fallowed for one year.

These are known to affect the preferential flow water (Ouattara et al., 2007; Petersen et al., 1997, Sanou et al., 2010) depending on the soil type and the method of tillage. Tillage can result in more matrix flow in the upper part of the soil (Petersen et al., 1997; Jarvis et al., 2007). Fallowing may improve the soil structure and the activity of soil macro fauna and enhance infiltration (Sarr et al. 2001).

The dye infiltration patterns in tree with termite nest have variation between sampling points. Some sampling points have big channels with obvious heterogeneous flow while in others the termite nest channels and its effect is less conspicuous in the profile. Léonard et al. (2004) showed that the effect of termite on infiltration can vary in space and time such as termite macropores may be closed or open.

6. Conclusion

The results showed that trees with as well as without termite nests have significant effect on preferential flow in agroforestry parklands. The degree of preferential flow significantly decreased with increase in distance from the nearest tree and termite nests to the openings.

Preferential flow in small openings was significantly higher than the large openings with absolute slope parameter and close to significance with uniform front depth. The preferential flow in trees without termite nests was less conclusive compared to the openings, significantly higher with absolute slope and not with other parameters.

In contrast to the hypothesis, preferential flow in tree with termite nests and without did not show significant difference. Water inflitrability was not significant with treatment effect and distance from tree with termite nests and without to the openings. Trees and termites in agroforestry parklands improve preferential flow and may contribute to groundwater recharge.

Parameters that take into account the whole infiltration pattern and detailed information, like the absolute slope sum, come out as better predictors of the degree of preferential flow and the opening size effect than other parameters. Separate analysis based on the differences in land use, tree size and parameters that extract detailed information may provide a clear impression of the trees and termites role on preferential flow in agroforestry parklands.

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Appendix 1: Correlations beween parameters: Totsa(total stained area) ; Dye coverage (dycov(%); uniform front depth (unifrd); preferential flow fraction (pr-fr); totalroots(torots); total big macropores (totbigmac); peak index(peakindex);absolute slope(absslope);standard Deviation index(SD index)

	Totsa	Dycov(%)	unifrd	pr-fr	torots	totbigmac	peakindex	abs slope	SD index
Dyecov.(%)	0,998								
	0,000								
unifrd	0,890	0,879							
	0,000	0,000							
pr-fr	-0,738	-0,727	0,940						
	0,000	0,001	0,000						
totrots	-0,328	-0,274	-0,376	0,323					
	0,184	0,272	0,125	0,191					
totbigmac	-0,492	-0,452	-0,611	0,595	0,842				
	0,038	0,060	0,007	0,009	0,000				
peakindex	-0,025	0,007	-0,411	0,529	0,393	0,494			
	0,922	0,977	0,090	0,024	0,106	0,037			
absslope	-0,722	-0,693	-0,854	0,826	0,473	0,552	0,432		
	0,001	0,001	0,000	0,000	0,048	0,018	0,073		
SD index	-0,366	-0,351	-0,589	0,687	0,241	0,351	0,611	0,474	
	0,136	0,153	0,010	0,002	0,335	0,153	0,007	0,047	

Cell Contents: Pearson correlation

P-Value

SENASTE UTGIVNA NUMMER

2012:5 Författare: Tomas Jansson
Estimation of reindeer lichen biomass by image analysis

2012:6 Författare: Axel Eriksson
Röjningsformens effekt på tallens (*Pinus sylvestris* L.) tillväxt och kvalitetsegenskaper

2012:7 Författare: Björn Henningsson
Inverkan av röjning och gödsling på mikrofibrillvinkeln i tallens (*Pinus sylvestris* L.) ungdomsved

2012:8 Författare: Sophie Casetou
The inter- and intra- specific variability of charcoal traits in boreal ecosystems

2012:9 Författare: Andreas Hagenbo
Allelopathic effects of Calluna vulgaris on Pinus sylvestris and Populus tremula

2012:10 Författare: Mikael Öhman
Utveckling av ett GIS-verktyg för selektion av bränningstrakter – en studie genomförd på SCA-skogs marker inom Medelpads skogsförvaltning

2012:11 Författare: Klara Joelsson Hedemyr
Soil organic carbon and infiltrability in relation to distance from trees (*Vitellaria paradoxa*) with and without termite mounds in a parkland of central Burkina Faso

2012:12 Författare: Felicia Olsson
Tame animals in the wilderness – livestock grazing around summer farms in Jämtland, boreal Sweden 1800-2011

2012:13 Författare: Jonas Sjödin
Undersökning av självspridning av contortatallen i norra Sverige

2012:14 Författare: Nils Henriksson
Measuring N uptake and transport in *Pinus sylvestris* to estimate mycorrhizal transfer efficiency. A tracer/fertilizer experiment in northern Sweden

2012:15 Författare: Mikael Sörhult
Influence of prescribed burning and/or mechanical site preparation on stand stem density and growth of Scots pine stands above the Arctic Circle: - results 9-19 years after stand establishment

2012:16 Författare: Per-Olof Nordin
NPK+ och blå målklassning – indikatorer på vattenkvalitet?

2012:17 Författare: Erik Söderbäck
Utvärdering av markberedning och plantering på SCA:s mark i Norrland 1998-2001. Föryngringsresultat efter 10 år

2012:18 Författare: Erik Söderholm
Lämpliga hybridaspkloner för odling i södra och mellersta Norrland

2012:19 Författare: Caroline Pöntynen Boström
Röjningsplan för Sveaskog

2012:20 Författare: Robyn Hooper
Climate change impacts and forest management adaptation measures in Sweden and British Columbia, Canada: A case study of Swedish forest managers

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